Relevance of CO2-based IAQ indicators: Feedback from long-term monitoring of three nearly zero-energy houses

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Abstract

There are a large number of indicators that use CO_2 concentration as parameter to assess air stuffiness and, consequently, to asses IAQ. Their comparison is difficult since they are not usually linked to each other. The aim of this article is to compare the results of 10 CO_2-based IAQ indicators and determine if they classify a house in a similar way during heating seasons. We propose a method to normalize the results based on the reference values of each indicator, and we highlight the sensitivity of the indicators to the choice of one occupancy scenario among several possibilities. The database used contains the CO_2 concentration measured over 2-3 years in the living room and the parental bedroom of three new and occupied nearly-zero energy houses in France (COMEPOS project) with low-cost probes sampling every minute. The results indicate that the IAQ of the same house in the same heating season can be classified differently depending on the indicator and threshold chosen. Moreover, an indicator can show different results for the same room over the years. For example, the IAQ of the bedroom of House 2 is

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classified poor in 2017 and 2019 but good in 2018 according to the mean CO_2 concentrations with a 1000-ppm threshold. The indicators also present different levels of sensitivity to occupancy scenarios, being the cumulative exposure the most sensitive by increasing up to 257% without an occupancy scenario, which highlight the importance of the systematic implementation of a standard occupancy scenario for the CO_2-based IAQ performance indicators.

Keywords

Indoor Air Quality (IAQ), CO_2, performance indicators, occupancy scenario, nearly zero energy houses.

1. Introduction

As people start to spend more time at home, it is important to consider the indoor environmental quality (IEQ) of their dwellings. There are warnings that energy-retrofitted buildings can present risks for the health of inhabitants related to the IEQ (Ortiz et al., 2020). Indeed, as for positive, zero and nearly-zero energy buildings, those buildings tend to be air tighter, reducing air infiltrations. If they are not equipped with efficient and well-maintained ventilation systems, indoor pollution can become high and molds are prone to appear.

The assessment of IEQ is complicated by the lack of consensus regarding measurement protocols, category weighting schemes, and assessment class limitations (Heinzerling et al., 2013). Therefore, the performance of the same building can be different depending on the regulations and the evaluator’s interpretation.

Analyses of recent results of an experimental campaign in a zero-energy building (Danza et al., 2020) and in multi-unit residential buildings (Andargie et al., 2019) showed that IEQ mainly depends on the indoor air quality (IAQ). However, the IAQ is a complicated issue. Despite the fact that IAQ parameters such as the concentration of CO_2, particle matter and volatile organic compounds are measureable and have effects on human wellbeing, there are no agreed measures that can quantitatively describe the IAQ and that will facilitate the assessment of measures to improve energy performance (Salis et al., 2017).

A performance indicator is an assessment and decision support tool. It reports the particular situation or state of something based on certain parameters. Wei et al. (Wei et al., 2020) found nearly 100 parameters that are used in green building schemes to describe IAQ and the quality of the thermal, acoustic, and visual environment. It is complicated and impractical to measure all the parameters necessary to calculate the performance indicators of the different standards, especially given the difficulty of long-term monitoring of some of them without interfering with the normal activities of the inhabitants (e.g. formaldehyde and particle matter). Therefore, this article focuses on one parameter that has been widely used to this end: CO_2. In fact, several standards such as NF EN 15251, NF EN 15665 and NF EN 16798 (CEN, 2017; NF EN 15251, 2007; NF EN 15665, 2009) have proposed the measurement of CO_2 concentrations as a parameter for evaluating IAQ.

The CO_2 concentration is correlated with human respiration and air renewal (ANSES, 2013). As the body constantly produces CO_2, the presence of this compound inside buildings is an indicator of occupancy and air renovation due to ventilation. A high rate of CO_2 indoors is commonly accompanied by human bioeffluents (Zhang, Wargocki, & Lian, 2017). According to Zhang et al. (Zhang et al., 2016; Zhang, Wargocki, Lian, et al., 2017), the exposure to human bioeffluents and CO_2 concentrations around 1600 ppm at a ventilation rate of 4.10^{-3} m^3s^{-1} per person cause sensory discomfort but it do not cause negative effects on cognitive performance or acute health symptoms. However, other studies suggest that at CO_2 concentrations of 1000 ppm there is a moderate decrease in decision-making performance (Jaber et al., 2017; Satish et al., 2012).

The concentration of CO_2 indoors also facilitates the calculation of air stuffiness indicators (Persily, 2017; Ribéron et al., 2016). A high level of air stuffiness indicates an air renewal unsuited to the occupancy density of the site and thereby signifies a possible accumulation of other substances emitted inside the building. Thus, the identification of a highly confined space using CO_2 concentrations can potentially indicate the presence of other substances, such as certain gaseous compounds or bio-aerosols, which can degrade the IAQ.

Currently, there are numerous CO_2-based IAQ indicators and their description is often ambiguous, since not all of them have reference values, a concrete period, a time step, and a specific place for taking the measurements. Even rarer is finding indicators that include occupancy scenarios. Standards such as NF EN 15251 and NF EN 16798 (CEN, 2017; NF EN 15251, 2007) indicate that CO_2 measurements should be made where it is known that occupants spend most of their time, preferably in winter, but they do not include the sample size or the time step to guarantee the quality of the results.

The measurement periods of recent studies carried out in inhabited residential buildings are quite varied: one week or less (Cheung & Jim, 2019; Leivo et al., 2016; Wang et al., 2016), one month (Caro & Sendra, 2020), one year (Dai et al., 2018; Huang et al., 2018, 2020), more than one year (Belmonte et al., 2019; Derbez et al., 2014; Du et al., 2015; Liu et al., 2018), some days in different seasons of the same year (Serrano-Jiménez et al., 2020) and some days at the same season but different year (Hesaraki et al., 2015; Pungercar et al., 2021). The measuring range and time step of the probes are also different between studies: the minimal measure is 0 or 400 ppm, the maximal measure varies from 2000 to 10000 ppm, and the time step varies from 1 to 30 min.

With the aim of contributing to a future consensus on the CO_2-based IAQ indicators for characterizing residential buildings, the present paper focuses on knowing if the different indicators classify a house in a similar way during a certain period by:

1.Testing several CO_2-based IAQ indicators selected from the literature, standards and regulations, such as the air stuffiness index (ICONE), the mean concentration, and the cumulative exposure,

2. Proposing a method to normalize and compare the indicators results, and

3. Highlighting the sensitivity of the indicators to the choice of one occupancy scenario among several possibilities.

The database used in this study comes from a long-term measurement campaign (between 2 and 3 years) in three real and occupied, nearly zero-energy houses in France built within the framework of the "Optimized design and construction of positive energy houses" project (COMEPOS project) (CEA-INES, 2021).

2. Materials and methods

2.1. Case studies: three low-energy houses

Samplings and measurements were conducted in three new and occupied nearly-zero energy houses located in the Alps and Paris regions in France; the characteristics and plans of the houses are presented in Table 1 and Figure 1, respectively. The selected periods are the heating seasons between November 1 and April 15 from 2017 to 2020. These dates were chosen based on the degree–day (Park et al., 2021) of the 3 years corresponding to the periods when we note the presence of heating related to electricity consumption in House 1. In this study, only heating seasons are considered because these are the periods in which CO_2 concentrations are highest inside dwellings and the opening of windows influences less the ventilation. In addition, it is the period usually recommended by the standards and regulations (CEN, 2017; Guyot et al., 2018a; NF EN 15251, 2007).

Table 1: Characteristics of COMEPOS houses.

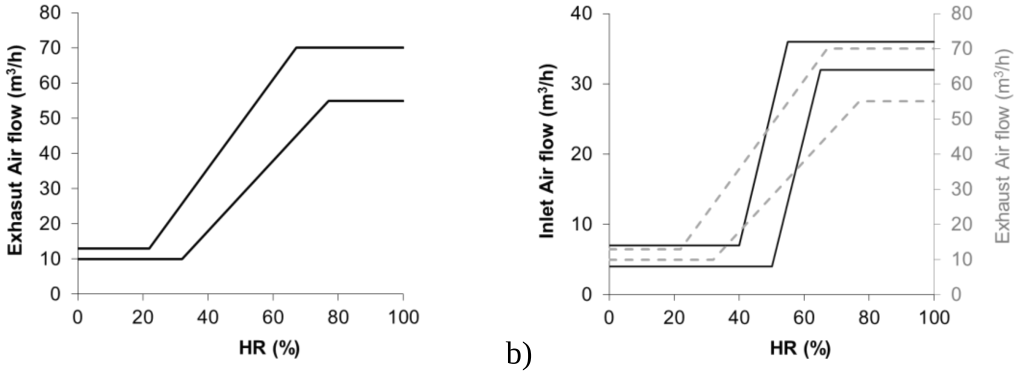
	House 1	House 2	House 3
Location	Alps region	Paris region	
Climate zone *	Cold (H1c)	Cold (H1a)	
End of construction year	2016	2017	2017
Total area	123 m^2	106 m^2	147 m^2
Number of bedrooms	3	4	4
Number of humid rooms	4	3	5
Living room area	40 m^2	40 m^2	40 m^2
Parental bedroom area	15 m^2	9 m^2	26 m^2
Construction materials	Cement chipboard with thermal insulation in walls, floors and roof		
Heating system	Radiant floor heating	Inertia radiators	
Ventilation system	Humidity-controlled ventilation B type + supply vents controlled by RH and CO_2 rates in living room and parental bedroom	Humidity-controlled ventilation B type	
Inhabitants	2 adults and 1 child	2 adults and 1 child (2018) 2 adults and 2 children (2020)	2 adults and 3 children
Occupancy data	Bedroom windows half-open at night	An adult is not present every day because of his work A child was born in 2020	An adult work at night

* Climate zone according to the French thermic standard RT2012 (Ministère de la transition écologique, 2021). H1 corresponds to the coldest zone of France (northeast) composed by 3 regions (a, b and c).

Figure 1: Plans of the study houses.

2.1.1. Smart ventilation systems

The three houses have demand-controlled ventilation (DCV) systems that are considered smart ventilation systems according to the definition given by Durier et al. (Durier et al., 2018). Houses 2 and 3 have a humidity-controlled exhaust-only ventilation system, which is one of the reference systems in France: New air enters through humidity-controlled air inlets located in the bedrooms and living room, and is extracted in humid rooms equipped with humidity-controlled exhaust vents, except in toilets where occupancy sensors are used. The extensions and retractions of a hygroscopic fabric modify the cross-section of inlets (trickle ventilators on windows) and exhaust vents on relative humidity (RH), and thus no electronic sensor is used. Figure 2 shows the airflows provided by exhaust vents and inlets as a function of RH. For low RH, minimum airflows of approximately 10 $m^3.h^{-1}$ are maintained in order to dilute other pollutants from the building materials and furnishing such as VOC, as required by the French ventilation regulations (Arrêté du 24 mars 1982 relatif à l'aération des logements, 1983). Jardinier et al. (Jardinier et al., 2018) further described this ventilation system. The in situ performances of the ventilation system have not been checked and measured at this stage in the two houses.



a) b)

Figure 2: a) Exhaust unit hygroscopic curve envelope. b) Inlet hygroscopic curve envelope (black curve). Source : (Jardinier et al., 2018)

In House 1, an innovative smart ventilation system was tested: the same humidity-controlled exhaust-only ventilation system as in Houses 2 and 3 was installed and coupled with CO_2-sensor supply vents in the living room (LR) and the parental bedroom (PBR). These supply vents operate only when the RH is greater than 50% or when the CO_2 concentration is greater than 1000 ppm.

The COMEPOS database do not include information about the in situ performances of the ventilation system such as flow rates, pressure differences or correct RH/CO_2 changes in trickle vent inlets. However, we obtained information from the inhabitants and constructors. In House 1, a trickle ventilator not operates correctly because of the absence of mortise in the window jambs. In addition, the inhabitants of House 1 turned off the CO_2-controlled supply vent in the PBR and indicated that they always leave the windows half-open in this room, including during winter periods. There are no reports of ventilation system malfunctions in Houses 2 and 3.

2.1.2. IAQ sensors

The three houses are equipped with the E4000 NanoSense probe (Nanosense, s. d.) for measuring temperature, RH, and CO_2 concentration. According to the manufacturer's specifications, the measuring range and the accuracy are [0–50°C] and ±0.3°C for the temperature sensor, [10–90%] and ±3% for the RH sensor, and [390–3500 ppm] and ±100 ppm at 25°C and 1013 mbar for the CO_2 sensor. The data acquisition time is between 2 and 3 years, with a time step of 1 min.

At the beginning of the study, the three houses were equipped with electro-chemical CO_2 sensors. However, the sensors in House 1 had anomalies and were replaced by NDIR (Non-Dispersive Infra-Red) sensors. The data collected before the change was deleted, which is why House 1 only has two heating seasons.

The European commission (Gerboles et al., 2017) warns of the limitations of the use of low-cost sensors arguing that, at their current stage of development, they are less performant than official monitoring stations. The commission also explains that the CO_2 low-cost sensors have a good sensitivity in a range from 350 to 2000 ppm, and a limited drift over time of the sensor calibration.

All probes were calibrated and monitored by the COMEPOS project partners. In this study we only use and exploit the data. Looking to the minimum value of CO_2 in both LR and PBR, we check that there was not drift of the sensors. Indeed, the minimum values correspond to periods with open windows or long unoccupied periods. This minimum values are maintained in the three houses throughout the years, around 395 ppm.

2.2. Data analysis and quality validation

In order to remove parasitic measures that can significantly affect the study results, we treat the data according to the three steps shown in Figure 3:

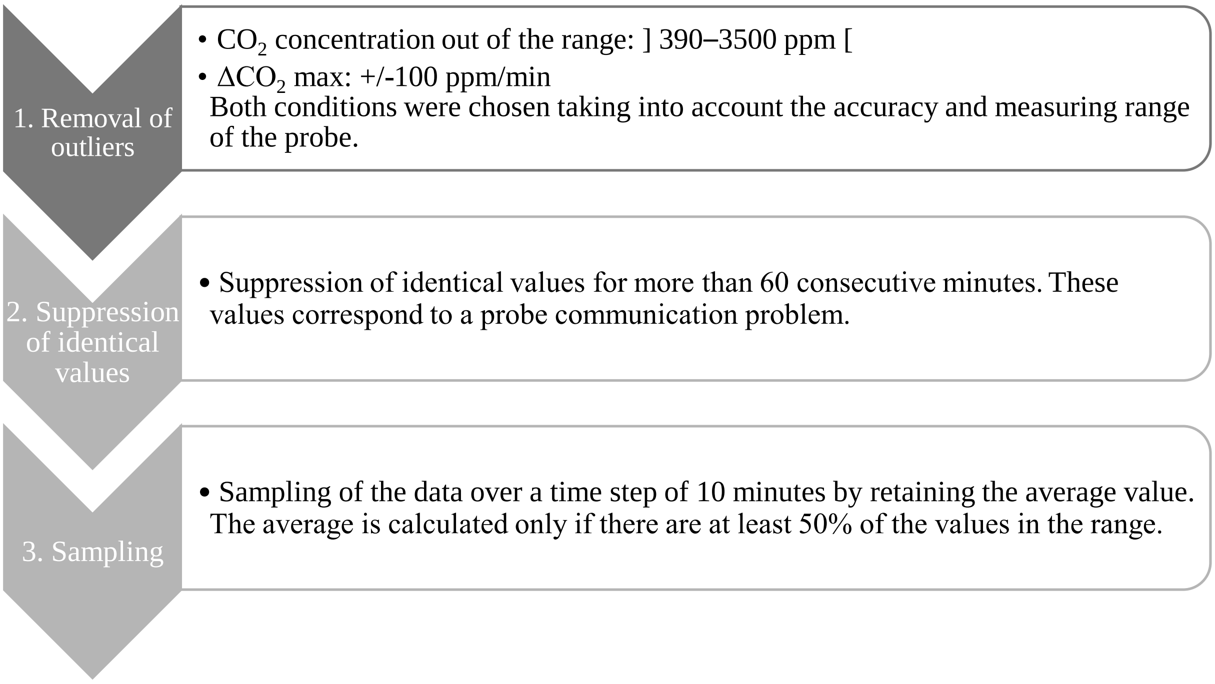


Figure 3: Treatment steps for the CO_2 measurements.

We calculate the percentage of data available before the treatment (%DBT) and after the treatment (%DAT), for every study period (

Table 2). The %DBT is calculated as the ratio of the values available before treatment over the total expected values. It shows how many data are obtained by the low-cost captors but also the extent to which the measurements are representative of the period. These percentages are high, between 70 and 100%. The %DAT is the ratio between the values after treatment and the total expected values. It indicates how many of the initial data are usable. The difference between the %DBT and the %DAT implies that 11–51% of the data obtained by the captors is not exploitable. The %DAT ranges from 38 to 89% and is the indicator used in the rest of the analysis.

Table 2: Quantity of expected values and available values before and after treatment for the heating seasons in the COMEPOS houses. Percentage of data available before treatment (%DBT) and after treatment (%DAT). Time step of 10 min. Measures in living rooms (LR) and parental bedrooms (PBR).

House	Room	Heating season														
		2017–2018					2018–2019					2019–2020				
		Expected values	Values before treatment	Values after treatment	%DBT	%DAT	Expected values	Values before treatment	Values after treatment	%DBT	%DAT	Expected values	Values before treatment	Values after treatment	%DBT	%DAT
House 1	LR						23898	18150	12172	76	51	24042	23945	17791	100	74
	PBR						23898	18086	9107	76	38	24042	23924	16055	100	67
House 2	LR	23898	23632	19865	99	83	23898	23863	21161	100	89	24042	16861	10988	70	46
	PBR	23898	23634	15749	99	66	23898	23863	11702	100	49	24042	16861	10751	70	45
House 3	LR	23898	19782	16107	83	67	23898	22700	16340	95	68	24042	23680	18048	98	75
	PBR	23898	19788	16570	83	69	23898	22665	18494	95	77	24042	23747	19967	99	83

The probe installed in the COMEPOS houses can measure up to 3500 ppm but it is possible that this threshold was exceeded. The frequency graphs (Figure 4 and Figure 5) show that less than 2% of the values after treatment are greater than 3000 ppm during every heating season in the three houses. Therefore, the measuring range of the probe is sufficient for calculating the CO_2 concentrations without missing any critical information.

2.3. IAQ indicator calculation based on CO_2 measurements

Reference values or requirements are important to compare and frame the information provided by the indicators. In this context, the CO_2 concentration provided by the E4000 probe is the parameter that allows the calculation of several indicators reported in the literature. We compare the indicator values with the thresholds of different requirements and also compare the indicators against each other. With this method, we can identify the relevance of the indicators and the important thresholds for assessing the performance of houses.

We calculate the following 10 indicators taken from the analyzed literature, standards, and regulations, determined in the LR and the PBR during the heating seasons:

1. The mean concentration (Ministerio de Fomento, 2019; NF EN 15251, 2007; NF EN 15665, 2009) described in Eq. 1. This is the most common CO_2-based IAQ indicator used in recent studies in inhabited dwellings (Belmonte et al., 2019; Caro & Sendra, 2020; Cheung & Jim, 2019; Dai et al., 2018; Derbez et al., 2014; Du et al., 2015; Huang et al., 2018, 2020; Leivo et al., 2016; Liu et al., 2018; Pungercar et al., 2021; Serrano-Jiménez et al., 2020; Wang et al., 2016).
2. The mean concentration above a threshold value (NF EN 15665, 2009) described in Eq. 2.
3. The percentage of time spent in a concentration range (NF EN 13779, 2007; NF EN 15251, 2007), used in European studies (Guyot, 2018; Laverge et al., 2013). The

reference ranges chosen for the present study are also in accordance with standards NF EN 13779 (NF EN 13779, 2007) and NF EN 15251 (NF EN 15251, 2007) :

- IDA 1 (High IAQ) for concentrations inferiors to 750 ppm
- IDA 2 (Medium IAQ) for concentrations between 750 and 900 ppm
- IDA 3 (Moderate IAQ) for concentrations between 900 and 1200 ppm
- IDA 4 (Low IAQ) for concentrations superiors to 1200 ppm

4. Six types of cumulative exposures greater than a threshold value (BCCA, 2012; CCFAT, 2015; Guyot et al., 2018b; Laverge, 2013; Mansson, 2001; Ministerio de Fomento, 2019; NF EN 15665, 2009). The cumulative exposure greater than a threshold value indicator, which is similar to the notion of "dose," makes it possible to accumulate exposure beyond a threshold over a given period. While the dose is calculated for one person, this indicator is calculated at a room scale. It is widely used to assess the performance of intelligent ventilation systems, with distinctions depending on different countries (Guyot et al., 2018). Equations 3–8 describe the CO_2 cumulative exposure indicators and the corresponding threshold values if they are available, considering an average outdoor concentration of 350 ppm.

We note similarities between the cumulative exposure indicators in terms of construction:

- With E_{950} and E_{1600}, the integral is calculated by removing the values below the limits of each indicator (subscript number in the respective name), subtracting the same limit from the remaining values and multiplying by time. The result is compared with a constant threshold.

- With E_{1000} and E_{2000}, the integral is calculated by only removing the values below the limit (subscript number in the respective name) and multiplying by time. The result is compared with a threshold, variable for E_{1000} and constant for E_{2000}.
- With E_{1050} and E_{1750}, the integral is calculated in the same way as with the E_{1000} and E_{2000} indicators, but the result is compared with a range that offer a direct classification of the air quality (Table 3).

5. The ICONE air stuffiness index (Ribéron et al., 2016) described in Eq. 9, which is used in the mandatory control of IAQ in schools and nurseries in France. This index is calculated with the frequency of time spent in the concentration ranges, between 1000 and 1700 ppm and above 1700 ppm. The scale of the index goes from 0 to 5, where 0 corresponds to no stuffiness, 1 to low, 2 to medium, 3 to high, 4 to very high, and 5 to extreme stuffiness.

Some of these indicators have reference values for comparing the results, such as the E_{950}, E_{1000}, E_{1600}, and E_{2000} indicators. Others have ranges, e.g. the E_{1050} and E_{1750} indicators and the ICONE air stuffiness index. Indicators such as the mean concentration do not have a specific value for comparisons. Nevertheless, we can use as reference one of the most common CO_2-IAQ threshold values: 1000 ppm (ANSES, 2013; Von Pettenkofer, 1858). This value is coherent with recommended CO_2 thresholds used to prevent virus transmission during the Covid19 crisis, e.g. using a traffic light indicator based on CO_2 levels (a yellow/orange light is set to 800 ppm and a red light up to 1000 ppm) (REHVA Federation of European Heating Ventilation and Air Conditioning Associations, 2021). Other slightly different values have been applied in specific countries such as France (Haut Conseil de la santé publique, 2021) and Belgium (Task Force Ventilation, 2021).

For the specific case of the mean concentration above a threshold value indicator, we use 1000 and 2000 ppm as the threshold from which we will save the data to calculate the average (Guyot, 2018), but there are no threshold values for comparisons.

Complementary to these indicators from the literature, we also studied the frequency distribution of CO_2 concentrations by calculating the boxplot and the kernel density using the kdeplot function of the Seaborn Python library. In the boxplot, the sides of the box represent the first and third quartile (50% of the data are located here) while the length of the whiskers is 1.5 times the interquartile difference. The size of the boxplot rectangle, the interquartile range (IQR), illustrates the dispersion of the data. The kernel density provides an estimate of the density at any point from the smoothing of histograms. This last representation makes it possible to detect peaks of concentration that are not visible in the boxplot. However, it involves a parameter adjustment resulting from the smoothing: over- or under-smoothing can alter meaningful values of the distributions, especially the extreme values.

Eq. 1	$C_{co_2\,avg} = \frac{\sum_i C_{co_2}(t_i)}{\sum_{tot} i}$	(Ministerio de Fomento, 2019; NF EN 15251, 2007; NF EN 15665, 2009)
Eq. 2	$C_{avg\,co_2 > threshold} = \frac{\sum_i C_{co_2} > threshold(t_i)}{\sum_{tot} i}$	(NF EN 15665, 2009)
Eq. 3	$E_{950} = \sum_{t=0}^{T} \left(C_{CO_2>950ppm}(t) - 950ppm\right) \cdot t < 100\,000 \text{ ppm.h}$	(BCCA, 2012)
Eq. 4	$E_{1000} = \sum_{t=0}^{T} \left(C_{CO_2>1000ppm}(t)\right) \cdot t < 1000 \text{ ppm} \cdot X$	(Guyot et al., 2018b; Laverge, 2013)
Eq. 5	$E_{1050} = \sum_{t=0}^{T} (C_{CO_2>1050ppm}(t)) \cdot t$	(Mansson, 2001)
Eq. 6	$E_{1600} = \sum_{t=0}^{T} (C_{CO_2>1600ppm}(t) - 1600ppm) \cdot t < 500\,000 \text{ ppm.h}$	(Ministerio de Fomento, 2019)
Eq. 7	$E_{1750} = \sum_{t=0}^{T} (C_{CO_2>1750ppm}(t)) \cdot t$	(Mansson, 2001)
Eq. 8	$E_{2000} = \sum_{t=0}^{T} (C_{CO_2>2000ppm}(t)) \cdot t < 400\,000\ ppm.h$	(CCFAT, 2015)
Eq. 9	$ICONE = 8{,}3 \log(1 + f_1 + 3f_2)$	(Ribéron et al., 2016)

$C_{CO_2}: CO_2\ concentration\ in\ ppm$
$f_1: proportion\ of\ C_{CO_2}\ between\ 1000\ and\ 1700\ ppm$

f_2: $proportion\ of\ C_{CO_2}\ above\ 1700\ ppm$
t: $time\ in\ hours$
X: $measurement\ acquisition\ duration\ or\ simulation\ duration\ in\ hours$

Table 3: Reference values for E_{1050} and E_{1750} indicators. Source: adapted from (Mansson, 2001).

Stuffiness	CO_2 Cum. exp. > 1050 ppm (ppm.h)	CO_2 Cum. exp. > 1750 ppm (ppm.h)
Low	500 000	100 000
Medium	1 000 000	200 000
High	2 000 000	500 000
Very high	4 000 000	1 500 000

Most of the performance indicators have been used in a design context, at the design stage of a building or to assess the theoretical performance of innovative systems. The proposed thresholds have been suggested for an entire simulated heating season and must be adapted to a measurement context, where many data could be missing or removed during the treatment process.

Nearly all these indicators can be calculated either over the total heating period or by using only the exposure periods, when occupants are in the rooms. Since these data are not necessarily available, or are not precise enough, we need to use occupancy scenarios. The consideration of a scenario is critical because it can mitigate the underestimation of certain indicators, such as the average concentration or the cumulative exposure, if it is representative of the inhabitants' habits. Thus, in order to analyze the sensitivity of each indicator to occupancy scenarios, we tested three scenarios during the whole week: "no scenario," "standard scenario," and "adapted scenario" (Table 4). The standard scenario is derived from an analysis of the literature (Guyot, 2018; Zeghnoun et al., 2010). We defined the adapted scenario based on the daily study of CO_2 concentrations in the LR and PBR of House 3 between 2018 and 2020. In fact, the adapted scenario is close to the standard scenario with 2 h more in the LR and 1 h and 20 min more in the PBR.

Table 4: Occupancy scenarios for the calculation of IAQ indicators based on the CO_2 concentration measurement. Weekdays and weekend included.

No scenario	Standard scenario	Adapted scenario
All hours included	Living room: 07h00 to 08h30 12h00 to 14h00 19h00 to 21h00 Bedroom: 21h00 to 06h20	Living room: 06h00 to 09h00 12h00 to 13h30 18h30 to 21h30 Bedroom: 22h00 to 06h00

2.4. Comparison method of CO_2-based IAQ indicators

A comparison of the results from the various indicators is complicated because each indicator is different in nature (discrete, normalized, etc.) and has different reference values – as explained before, some have reference values for comparison, others have ranges of values, and others neither of the two. In order to compare the results obtained for the same house in the same room during the same heating season with different indicators, we propose the following method to normalize the results:

- For the indicators with a reference value (mean concentration, E_{950}, E_{1600}, and E_{2000}), we calculate the ratio between the indicator value and the associated reference value.
- For the indicators with a range of values (E_{1050}, E_{1750}, and ICONE), we take the class of stuffiness assigned (no stuffiness, low, medium, high, very high and extreme) and then we transform the class to a numerical result according to Table 5. This new classification is based on the principle that reaching the reference value indicates a degraded IAQ but not to the point of extreme stuffiness. Then, a value of 1 signifies that the indicator result is equal to the threshold and the stuffiness is medium, a value less than 1, a low confined space, and a value greater than 1, a confined space.

- The indicators that do not have reference values or a range for comparison cannot be normalized using this method and are therefore not included in the comparison. These indicators are the mean concentration above a threshold value and the percentage of time spent in a concentration range.

Table 5: Proposed classification to normalize the results from indicators with ranges for describing the stuffiness in a room.

Stuffiness	**Default value assigned**	**Description**
No confinement	0	Value<Threshold
Low	0.5	Value=Threshold/2
Medium	1	Value=Threshold
High	1.5	Value=1.5 Threshold
Very high	2	Value=2 Threshold
Extreme	2.5	Value=2.5Threshold

After normalizing the results, we plot them on a radar in order to visualize the magnitude of the differences. It is important to mention that we found this to be a pertinent method for comparing the results but there are also other ways to compare them.

To quantify the sensitivity of the indicators to the occupancy scenarios, we define the sensitivity as the relative difference between the CO_2-based IAQ indicators calculated with the standard scenario and those calculated with the other scenarios (adapted and no scenario). We also present the normalized results of the indicators of the three scenarios on a radar.

3. Results and discussion

3.1. IAQ results for the selected CO_2-based performance indicators calculated with the standard scenario

3.1.1. Distribution of CO_2 concentrations

In order to clarify the presentation of the results and to describe the overall behavior of the CO_2 concentration inside a dwelling, we use frequency distribution calculations with kernel densities

(a) and boxplots (b), for the LR (Figure 4) and the PBR (Figure 5) in each house during each heating season.

The results are presented in three stages: comparisons between the three houses, between the LR and the PBR, and between the heating seasons.

- **Comparison between the three houses**

Logically, there is a significant difference in the distribution of CO_2 concentrations between the three houses. The size and location of the boxplots in Figure 4b and Figure 5b reflect these differences. The boxes are considerably shorter, illustrating a lower dispersion of the CO_2 concentration, being closer to the low concentration values in House 1, in both the LR and in the PBR, than in Houses 2 and 3.

The minimal concentration is similar in all cases, around 400 ppm, which is close to the outside concentration. This minimal value is visible in the boxplots but not in the curves of the kernel densities: Houses 2 and 3 have values below 390 ppm (lower limit of probe measurement) due to the smoothing of the histograms. This shows that kernel density makes it possible to distinguish the shape of the distribution and its type (unimodal, bimodal, or multimodal) but that the extrapolation of the distribution leads to erroneous extreme values that must not be taken into account.

House 1 has a supply vent in both the LR and the PBR controlled by the CO_2 with a high rate activated as soon as the CO_2 concentration reaches 1000 ppm. This explains the low levels of CO_2 observed in the LR but not in the PBR. In the PBR, the inhabitants report that they sleep with the windows half-open at night, therefore the ventilation system has no influence in this room. The median concentrations are 482 and 488 ppm in the LR and 632 and 687 ppm in the PBR with an IQR of 98 and 95 ppm and 288 and 270 ppm, respectively. Houses 2 and 3 have a humidity-controlled ventilation system; the CO_2 concentration is therefore higher but remains acceptable.

Houses 2 and 3 have the same ventilation system, but with different characteristics since the number of rooms in each house is not the same (Table 1). Moreover, we do not have data at this time on the real in situ performances, as pressure differences at the exhaust vents have not been measured. Finally, the LRs in both houses have similar volumes but the PBR volume of House 3 is almost three times greater than that of House 2. Despite these differences, we observe similar median CO_2 concentrations in the PBR during the first season: 1159 and 1280 ppm, respectively (Figure 5b). The CO_2 concentration distribution data in LRs and PBRs of the three houses through the years is available in Table A1.

- **Comparison between the rooms: LR and PBR**

PBRs reached higher concentrations than LRs in all houses. The difference between the median value of the CO_2 concentrations in the LR and in the PBR (Figure 4b and Figure 5b) varies from 151 to 199 ppm over the 2 years in House 1, from 141 to 519 ppm over the 3 years in House 2, and from 106 to 443 ppm over the 3 years in House 3.

It seems reasonable to have higher CO_2 concentrations in the PBRs because the sources of CO_2 remain constant in this room (the two occupants sleep and stay there for several hours, usually with the door and windows closed) for a longer period than in the LRs.

- **Comparison between the heating seasons**

We observe changes in CO_2 concentrations between heating seasons both in the LR and in the PBR. These differences are particularly notable for the PBR of House 2 and House 3 (Figure 5b). Depending on the house, we note a variation of 8–35% in the median value and 6–65% in the IQR between the heating seasons in the same house. The maximal percentage of variation of CO_2-based IAQ results according to the indicators through years in LRs and PBRs is available in Table A2.

In the LR (Figure 4b), the differences between heating seasons are smaller. Depending on the house, we note a variation of 1–12% in the median value and 3–29% in the IQR between the heating seasons in the same house.

Considering an almost invariant external concentration of CO_2, the profile variations can be attributed to changes in the occupation habits of the inhabitants such as the birth of a child, hosting guests, vacations, frequency and duration of window openings, etc. Another explanation is that the ventilation airflows changed. Despite there is no record of modification or malfunction of the ventilation system reported by the inhabitants, except in the PBR of House 1, we cannot rule out the possibility of changes in the ventilation system without monitoring the pressures or airflows.

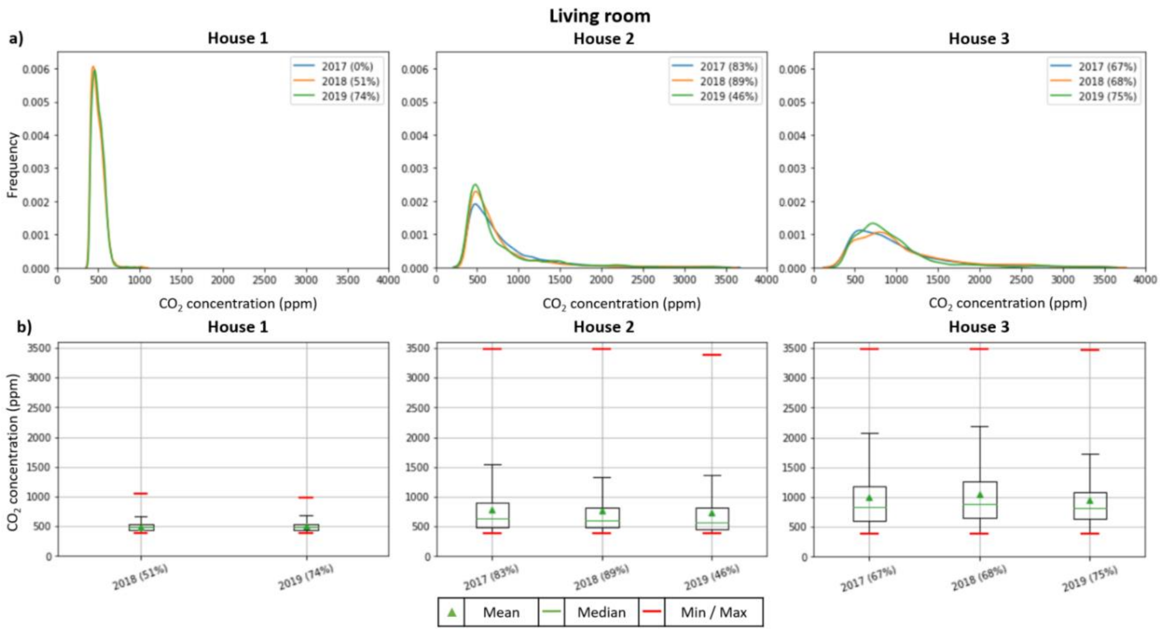


Figure 4: Frequency of CO_2 concentrations in the living room. The percentage in parentheses indicates the number of data available for the heating season after treatment (%DAT).

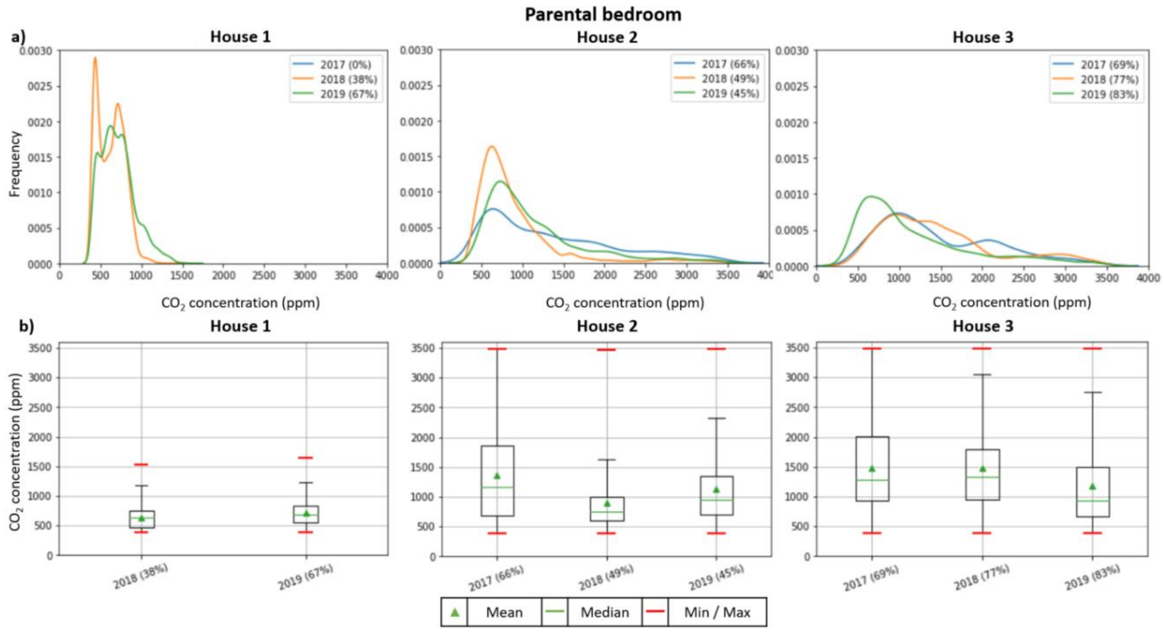


Figure 5: Frequency of CO_2 concentrations in the parental bedroom. The percentage in parentheses indicates the number of data available for the heating season after treatment (%DAT).

3.1.2. Mean CO_2 concentration

Figure 6 focuses on the mean CO_2 concentrations in the LR and PBR for each heating season. All the average values in the three houses, in the two rooms, and during the three heating seasons are in the range of [494–1482 ppm], lower than 2000 ppm. The threshold value used for this first analysis is 1000 ppm.

In House 3, the mean concentrations are close to the threshold in the LR with a range of [950-1058 ppm] during the three winters. In the PBR, the threshold is always exceed with a range of [1185-1482 ppm].

In the LR of House 2, the mean concentrations are below the threshold, with a range of [743–792 ppm] depending on the winter. In the PBR, the threshold is exceeded in 2017 and 2019 but not in 2018.

The threshold is not reached in both rooms of House 1, with mean concentrations of 494 and 498 ppm in the LR and 629 and 712 ppm in the PBR. The LR concentrations are very close to the outdoor concentration.

The differences found in the mean concentrations remain difficult to explain:

- Volumes: All the LRs have nearly the same volume.
- Ventilation systems: We need measurements or controls in situ to know how the systems truly operate. For instance, Houses 2 and 3 have the same ventilation systems but have a 23% difference in average concentration in the LR. Gaps between theoretical and real ventilation system performances could be a possible explanation.
- Occupancy: The highest CO_2 average concentration in the LR is observed in House 3, which seems logical because this house has the highest number of occupants. The PBR of House 2 presents the highest variations through the years (34%); this may be because one of the adults in this house has a job that requires travel, thus there are periods were the CO_2 sources are the half. With additional information about the daily occupancy schedules in the houses, we may conclude whether the occupancy could explain the concentrations measured.
- Inhabitants' habits: Common actions of the inhabitants such as opening a door or a window for a long time makes it difficult to know the effectiveness of the ventilation system because the evacuation routes of CO_2 increase.
- Percentage of data: It is difficult to have 100% of the data available using low-cost sensors, and thus it is important to consider the possibility of information loss.

We also observe that in the LR, the mean CO_2 concentration varies little during the seasons in the three houses, from 1 to 10%, in contrast to the PBR where these variations are more significant, from 12 to 34%.

The mean CO_2 concentration is higher in the PBR than in the LR regardless of the house and the season studied: a difference of 21–30% in House 1, 14–42% in House 2, and 20–32% in House 3.

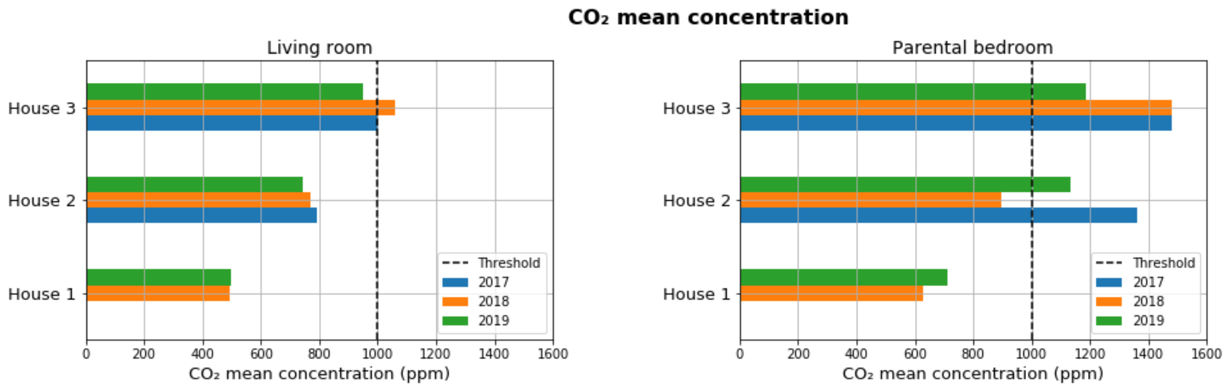


Figure 6: CO_2 mean concentrations in the living room and parental bedroom. 1000 ppm threshold value. Data of two heating seasons for House 1 (2018 and 2019) and three heating seasons for Houses 2 and 3.

3.1.3. Mean concentration above a threshold value

We calculate the mean value by excluding any value below a threshold (Eq. 2). Figure 7 presents the results using two thresholds: 1000 and 2000 ppm.

There is a significant difference between the RH-controlled ventilation houses (Houses 2 and 3) and the CO_2–RH-controlled ventilation house (House 1). The first two have similar mean concentrations above 1000 ppm in the LR, approximately 1500 ppm, despite the variation in the percentage of data available. A higher variation is present in the PBR, between 1500 and 1900 ppm. In House 1, concentrations are relatively close to the 1000-ppm threshold in the LR and the PBR.

The mean concentrations above 2000 ppm are similar between the LR and the PBR in Houses 2 and 3 during the different heating seasons, approximately 2500 ppm, with a maximal difference of 9%. There are no concentrations higher than 2000 ppm in House 1.

Using this type of indicator, we observe fewer differences between houses, between rooms, and between heating seasons than with the CO_2 average concentration indicator, except for House 1. The maximal percentage of variation of results through years in LRs and PBRs is available in Table A2. In House 1, the operation principle of the RH-CO_2-controlled ventilation system uses a control value of 1000 ppm to switch to a high ventilation rate, which is the same value as one of our selected threshold values. Here, we illustrate the issue of the choice of a threshold with some smart ventilation systems. To compare several houses with such a CO_2–RH system, we should select a threshold lower than the control value of the system.

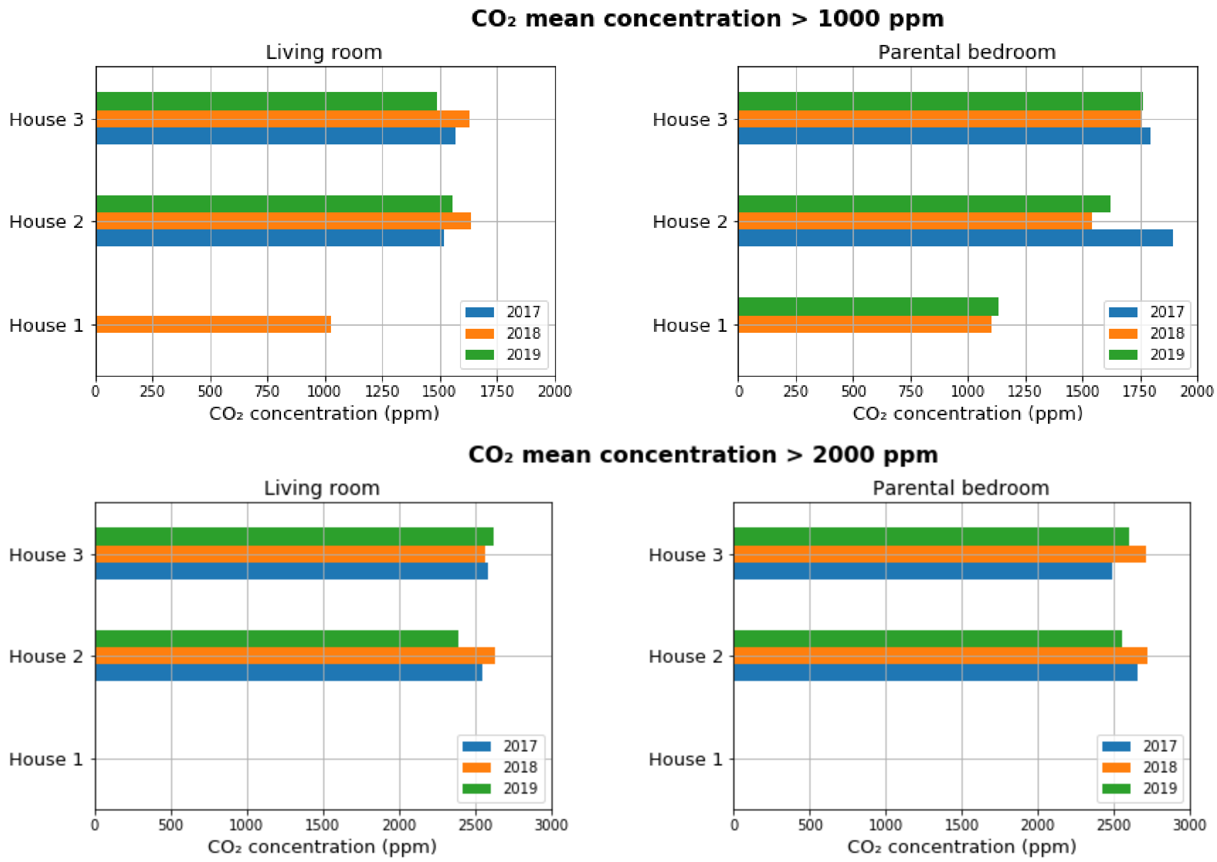


Figure 7: Mean CO_2 concentration above 1000 and 2000 ppm in the living room and the parental bedroom. Data of two heating seasons for House 1 (2018 and 2019) and three heating seasons for Houses 2 and 3.

3.1.4. Percentage of time spent in a concentration range

The percentage of time spent in a concentration range makes it possible to quantify the difference between the concentration distributions seen in Figure 4 and Figure 5. We calculate the percentage of time spent in different concentration ranges (IDA categories) in the LR and the PBR of the three houses (Table 6). We performed the calculations for all three winter seasons and give the range of the results.

- **Comparison between the three houses**

According to this indicator, House 1 has a high IAQ in the LR with more than 99% of the time spent in the IDA 1 category. On the other hand, Houses 2 and 3 have a significantly lower IAQ according to this indicator: the LR of House 2 was in the IDA 1 category 63–70% of the time, while for House 3 this was only 35–41% of the time depending on the year.

Regarding the percentage of time when the IAQ is considered low (IDA 4) in the LR, we note significant values in the RH-controlled ventilation houses: 12–13% of the time on House 2 and 18–28% of the time on House 3 depending on the year. However, in House 1 this percentage is zero because there are no values higher than 1200 ppm.

These findings imply that House 1 has the highest IAQ in the LR and House 3 has the lowest. The same trend is also seen in the PBR.

- **Comparison between the rooms: LR and PBR**

In the PBR, the percentage of time when the IAQ is qualified as high (IDA 1) is systematically lower compared with the LR regardless of the houses and the seasons considered: 25-39% on House 1, 19-40% on House 2, and 8-28% on House 3. Inversely, the percentage of time with low IAQ (IDA 4) is systematically higher in the PBR than in the LR: 0.1-3% on House 1, 3-35% on House 2, and 18-30% on House 3.

- **Comparison between the heating seasons**

There is no trend of growth or decrease in CO_2 concentration over the years on Houses 2 and 3. An example of this is the PBR of House 2 where the percentage of time corresponding to IDA 1 is 31% in 2017, 50% in 2018, and 30% in 2019.

Table 6: Range (min–max) of the percentage of time spent in a concentration range in the living room (LR) and the parental bedroom (PBR). Data of two seasons for House 1 (2018 and 2019) and three seasons for Houses 2 and 3.

	House 1		**House 2**		**House 3**	
	LR (%)	**PBR (%)**	**LR (%)**	**PBR (%)**	**LR (%)**	**PBR (%)**
IDA 1 (High)	99.4 - 99.7	60.5 – 74.2	62.8 – 70.1	30.0 - 50.0	35.2 – 40.6	11.3 – 32.9
IDA 2	0.2 - 0.3	22.0 – 23.4	9.2 – 11.8	8.1 – 16.8	15.4 – 17.7	10.3 – 15.1
IDA 3	0.1 – 0.3	3.7 – 13.6	7.7 – 12.3	13.2 – 20.8	19.7 – 23.6	16.0 – 22.1
IDA 4 (Low)	0.0	0.1 – 2.6	12.1 – 13.2	15.2 – 47.9	18.1 – 28.4	36.1– 57.7

3.1.5. Cumulative exposure greater than a threshold value

We apply a set of cumulative exposure indicators to the rooms under study (Figure 8). This indicator is calculated differently by using Equations 3–8, and has different thresholds for comparisons. The E_{950}, E_{1600}, and E_{2000} indicators have an invariable threshold, the E_{1000} indicator has a threshold that varies depending on the duration of the simulation, and the E_{1050} and E_{1750} indicators have a classification of results according to ranges.

- **Comparison between the three houses**

House 1 has a high IAQ according to each of the cumulative exposure indicators, with values well below the thresholds for E_{950}, E_{1000}, E_{1600}, and E_{2000}, and in the range of low stuffiness values for E_{1050} and E_{1750}.

Houses 2 and 3 have a variable IAQ depending on the indicator, on the room, and on the heating season studied. None of the houses reaches the thresholds proposed by E_{1000} and E_{1600}.

- **Comparison between the rooms: LR and PBR**

According to the results from this set of indicators, the stuffiness level is always higher in the PBR than in the LR. This difference is more notable in the RH-controlled ventilation houses than in the CO_2-RH-controlled ventilation house.

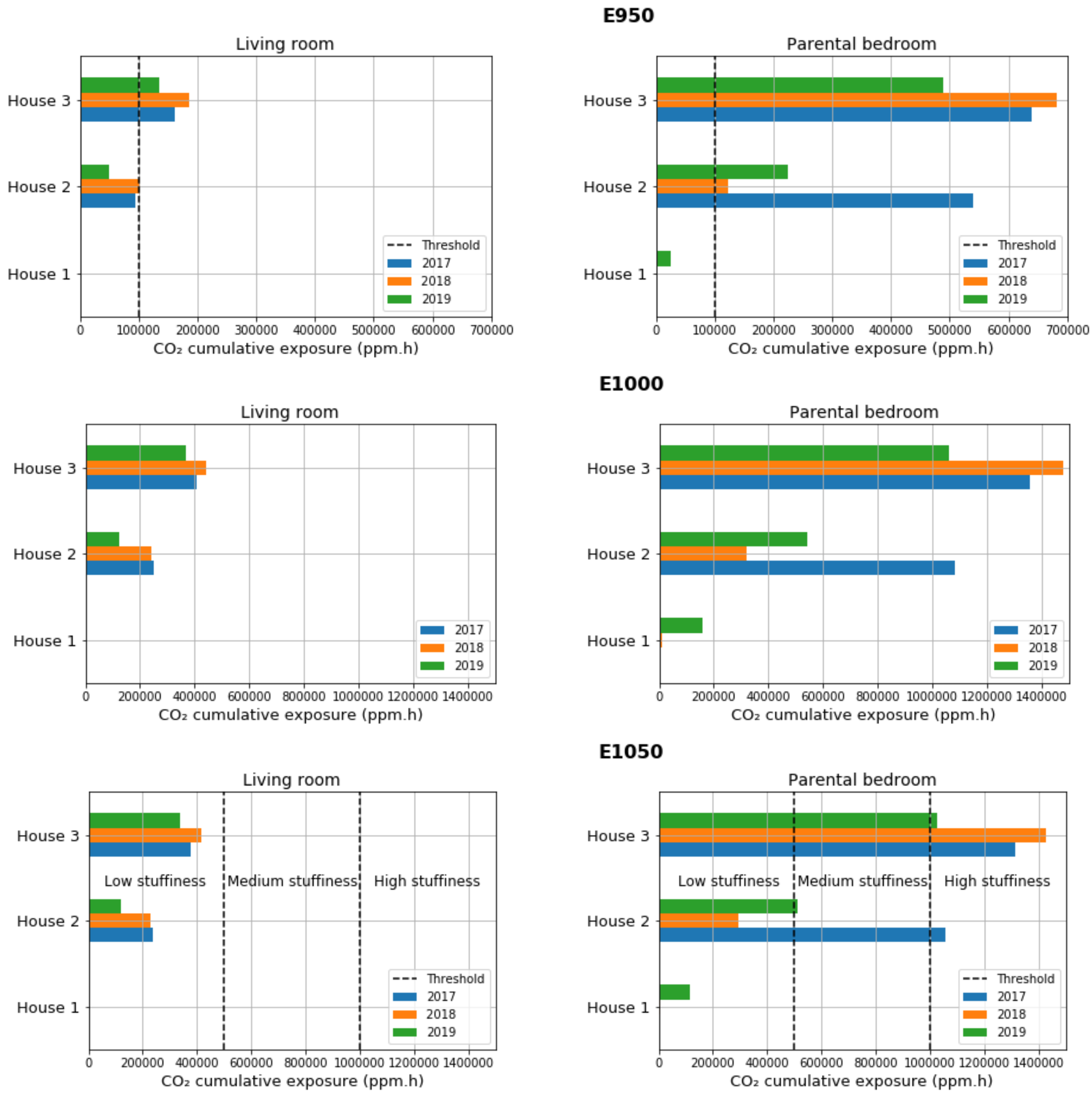
On House 1, the cumulative exposure values of E_{950}, E_{1000}, and E_{1050} are close to zero at the LR, which means a practically non-existent stuffiness. In the PBR, the same indicators have higher values but lower than their respective thresholds for E_{950} and E_{1000}, and in the range of low stuffiness for E_{1050}. There are no differences between the LR and PBR for E_{1600}, E_{1750}, and E_{2000}, all of them are zero. Therefore, both rooms in House 1 have a high IAQ according to the set of cumulative exposure indicators.

On House 2, the values corresponding to the LR are close to or lower than the threshold for E_{950}, E_{1000}, E_{1600}, and E_{2000}. In the case of E_{1050} and E_{1750}, the values are in the low stuffiness range or close to it. This means that there is agreement between all the cumulative exposure indicators that the IAQ is high at the LR of House 2. At the PBR the results vary more and the IAQ too. The E_{950} threshold is exceeded but the E_{1000} and E_{1600} thresholds are not. The E_{2000} threshold is exceeded only during one winter period (38%) and the E_{1050} and E_{1750} indicator values vary from low to very high stuffiness.

On House 3, the values corresponding to the LR are lower than the threshold for E_{1000}, E_{1600}, and E_{2000}. They are higher than the threshold for E_{950} and in the range of low and medium stuffiness for E_{1050} and E_{1750}, respectively. At the PBR they are lower than the threshold for E_{1000} and E_{1600}. The values are higher for E_{950} and E_{2000}, and in the range of high and very high stuffiness for E_{1050} and E_{1750}, respectively. This means that the IAQ at both rooms of House 3 can be classified differently depending on the indicator and the threshold chosen.

- **Comparison between the heating seasons**

There is a large difference between the results from the same indicator and house through the winter periods (Table A2). This means that a room can have a low stuffiness level (high IAQ) according to a specific indicator in one winter and a high stuffiness level (low IAQ) according to the same indicator in another winter. Taking the E_{1750} indicator at the PBR of House 2 as an example, we can see that the stuffiness level is very high in 2017, medium in 2018, and high in 2019. However, this behavior is not replicated with all indicators. There are indicators that yield the same classification results despite the large differences between seasons; this is the case for E_{1000} and E_{1600} where the thresholds are not reached and therefore the IAQ is classified as high.



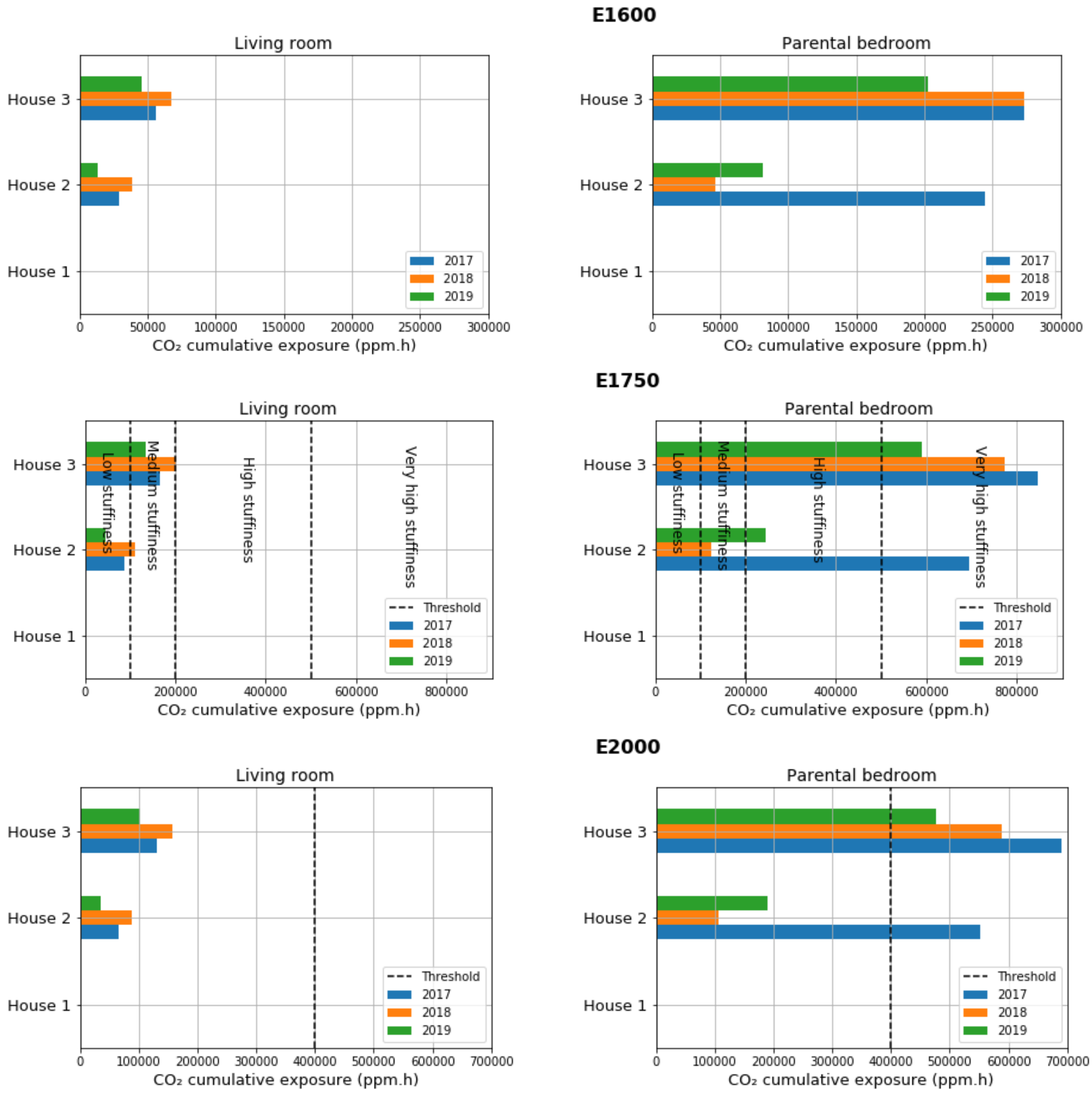


Figure 8: Cumulative exposure greater than a threshold value: E_{950}, E_{1000}, E_{1050}, E_{1600}, E_{1750}, and E_{2000}. Data of two heating seasons for House 1 (2018 and 2019) and three heating seasons for Houses 2 and 3.

3.1.6. ICONE Index

We calculated the ICONE air stuffiness index for the three houses, the two rooms, and the three heating seasons (Figure 9). All the ICONE index values are in the range of [0–3.1].

- **Comparison between the three houses**

According to the reference scale of ICONE values, we can conclude that House 1 has no air stuffiness, except at the PBR during the 2019 heating season where the value is low but not negative (0.4), which is consistent with the cumulative exposure indicators. By contrast, Houses 2 and 3 show a higher level of air stuffiness, in the range of [0.9–2.8] for House 2 and in the range of [1.4–3.1] for House 3. More precisely, House 2 has a low air stuffiness at the LR and variable air stuffiness (from low to high) at the PBR. House 3 has a medium level of indoor air stuffiness at the LR and a high level at the PBR.

- **Comparison between the rooms: LR and PBR**

As seen with previous indicators, we observe higher values in the PBRs than in the LRs. These differences are subtle in House 1 where both rooms have a final value of 0 during the two heating seasons. On Houses 2 and 3, the values at the PBR are 23–66% and 38–47% higher than at the LR, respectively. This time, the rooms of the same house during the same heating season tend to be classified in different categories.

- **Comparison between the heating seasons**

In the LRs, we see similar values between the heating seasons in each house, 0 on House 1 (no air stuffiness), approximately 1 on House 2 (low stuffiness), and approximately 1.5 on House 3 (between low and medium stuffiness).

In the PBRs, the stuffiness profile of the houses varies more than in the LRs. The PBR of House 2 has a high stuffiness level in 2017, low in 2018, and medium in 2019. The PBR of House 3 has a high stuffiness level in 2017 and 2018 and medium in 2019.

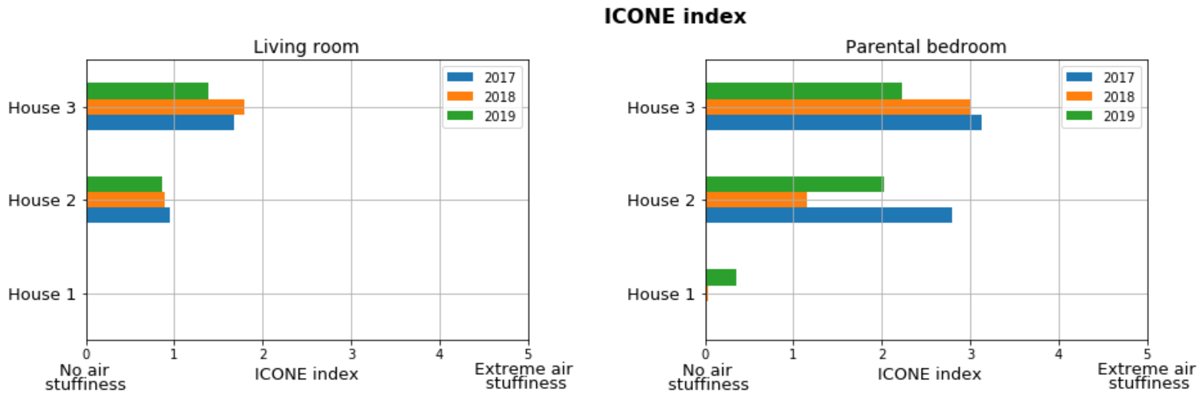


Figure 9: ICONE index values in the study houses on a scale from 0 "no air stuffiness" to 5 "extreme air stuffiness." Data of two heating seasons for House 1 (2018 and 2019) and three heating seasons for Houses 2 and 3.

3.2.Analysis of results and discussion on the relevance of indicators

The first results of this study show an approach to the assessment of IAQ through indicators based on the measurement of CO_2 concentrations in real and inhabited houses during several heating seasons.

Figure 10 show the results, after normalization, obtained with all the indicators that have a reference value or a range to classify the air stuffiness level of a room. The figure comprises six radars, each of them showing the results of one room in a specific house during the heating seasons (two heating seasons for House 1 and three for Houses 2 and 3). The scale is from 0 to 2.5 and the meaning of these values is provided in Table 5. Given that we calculate each of the indicators with respect to the same database and we normalize them according to the same method, which has two variants depending the type of indicator, we would expect to have similar results for each indicator during a particular heating season, that is, to observe concentric circles that represent the seasons in each of the radars. However, this is not the case for any of the radars. The indicators show different levels of stuffiness for the same room during the same heating season.

Firstly, the heterogeneity in the CO_2-based IAQ indicator results highlights that a house can be characterized as lightly confined by one indicator and highly confined by another. An example of this situation is the PBR of House 3, where we observe that the air has low stuffiness (close to 0.5) according to E_{1000} and E_{1600}, high stuffiness (close to 1.5) according to E_{1050}, and extremely high stuffiness (more than 2.5) according to E_{950}. Therefore, this questions the relevance of the indicators, their construction, and the reference values used to classify the IAQ.

We would expect to have similarities between the results of the indicators similarly constructed, but this is not always the case, especially between E_{950} and E_{1600}, where there was a greater difference. One explanation is the difference in the threshold chosen for each indicator. In fact, an indicator can be relevant but if the threshold is set at infinity, it will always yield the same qualification.

Secondly, our analysis shows the temporal variability of the results. A specific room in a house can be considered to have good IAQ according to a particular indicator during one heating season and a poor IAQ during another heating season according to the same indicator. An example is the PBR of House 2 where the E_{950} indicator shows a very high stuffiness level in 2017, a medium stuffiness level in 2018, and an extremely high stuffiness level in 2019.

The heterogeneity of the results found with different indicators for the same room during the same heating season can be explained by the disparity in the reference values of the different indicators (they are not linked to each other). The variation between houses and seasons is mainly due to (a) the particular habits of the inhabitants of each house (habits vary from one family to another, even within the same family), (b) the conditions of the immediate environment (climate, outdoor pollution, etc.), and (c) to the ventilation system installed.

One point to be analyzed is the relevance of the indicator calculations. Some indicators include information from other indicators in a direct or indirect way (Figure 11). In this study, we treat the frequency distribution concentrations through kernel density and boxplots; kernel density gives us direct information on the distribution of all concentrations, indirect information on specific values such as the mean, minimal, maximal, and median concentration, and no information concerning time (e.g., time exceeding a threshold). On the contrary, the boxplot representation gives us a less specific idea of the distribution but offers more precise data in terms of the specific values. Only the indicators of percentage of time spent in a concentration range and of cumulative exposure provide information about the amount of time that a threshold was exceeded. The ICONE index was created specifically for the measurement of stuffiness levels, and it is considered the only indicator that can give direct and precise information about the confinement level of a room.

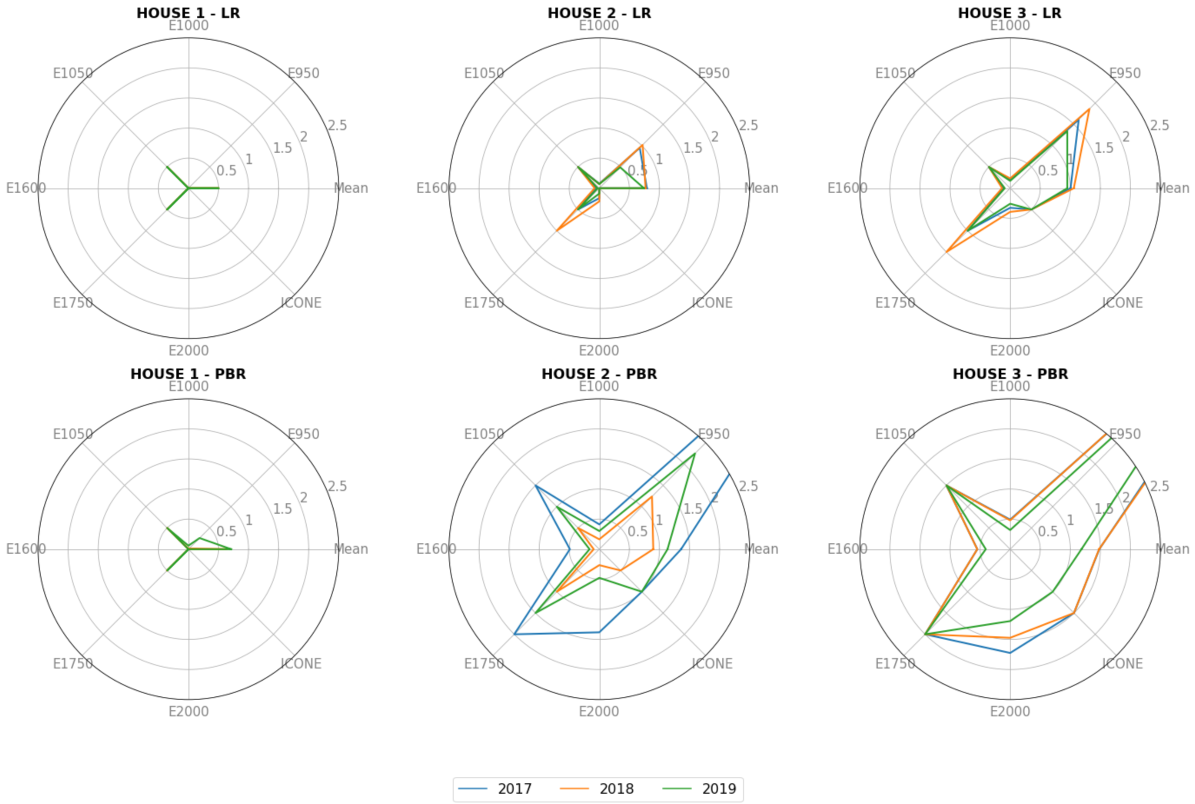


Figure 10: Radar showing the results, after normalization, of the CO_2-based IAQ indicators in the living rooms (LRs) and the parental bedrooms (PBRs) of three COMEPOS houses. Data of two heating seasons for House 1 (2018 and 2019) and three heating seasons for Houses 2 and 3.

Figure 11: Information provided by the CO_2-based IAQ indicators.

Indicator	CO_2 concentration information									
	Distribution	Mean *	STD	Min.	Max.	Median	Exceeding a threshold *			Air stuffiness
							Yes/No	Quantity	Time	
Frequency distribution by kernel density	Direct	Indirect	Indirect	Indirect	Indirect	Indirect	Direct	Indirect		Indirect
Frequency distribution by boxplot	Indirect	Direct	Indirect	Direct	Direct	Direct	Direct	Indirect		Indirect
Percentage of time spent in a concentration range	Indirect						Direct		Indirect	Indirect
Mean concentration **		Direct					Direct			Indirect
Mean concentration above a threshold value							Direct	Direct		Indirect
Cumulative exposure greater than a threshold value							Direct	Direct	Direct	Indirect
ICONE stuffiness index										Direct

Type of information	
(dark)	Direct
(light)	Indirect
(white)	Not available

* Information considered as an indicator.
** Possible hiding of overruns in short periods.

3.3. Study of the sensitivity of CO_2-based IAQ indicators to occupancy scenarios

We assess the relevance of restricting the period considered in the calculation of indicators and if it is necessary the use of a standard scenario. The house chosen for this study is House 3 because of the high number of good-quality data available (greater than 65%DAT). We define the sensitivity to occupancy scenarios as the relative difference between the calculated CO_2-based IAQ indicator and the same one calculated for the standard scenario.

Figure 12 presents the results, after normalization, of the CO_2-based IAQ indicators in House 3 with three different occupancy scenarios (no scenario, standard scenario, and adapted scenario) at the LR and at the PBR. The indicator of mean concentration above a threshold value is not included on this figure because it does not have reference values or a range for comparing the results. However, its sensitivity to occupation scenarios is taken into account on this analysis.

The indicators have different levels of sensitivity to the occupancy scenarios. The most sensitive type of indicator is the cumulative exposure that includes the E_{950}, E_{1000}, E_{1050}, E_{1600}, E_{1750}, and E_{2000} indicators. In fact, there is agreement in this set of indicators, which remove the data below the threshold specified in their name, that the absence of an occupancy scenario increases the values, by 215–257% at the LR and by 66–103% at the PBR. There is agreement that when applying an adapted scenario, the values increase at the LR, by 26–39%, and decrease at the PBR, by 9–11%.

The indicator less influenced by the occupancy scenario is the mean concentration above a threshold value, with a sensitivity in both rooms of ±3% for the no-scenario setting and ±1% in the adapted scenario. The simple mean concentration indicator has higher variations in the no-scenario setting than in the adapted scenario. Without a scenario, there is also a marked difference between rooms, a decrease of 7% at the LR and a decrease of 11–20% at the PBR.

This difference is less noticeable with the adapted scenario where both rooms have similar sensitivity, ±1% at the LR and an increase of 3% at the PBR.

Regarding the ICONE index, the difference from the standard scenario is also higher in the no-scenario setting than in the adapted scenario. Indeed, the results from the no-scenario setting reveal a decrease of 12–16% at the LR and of 16–25% at the PBR, while the maximum difference with the adapted scenario is 5% for the two rooms.

For some indicators such as the mean concentration and the ICONE stuffiness index, the LR seems less sensitive than the PBR. Unlike in the cumulative exposure greater than a threshold value set, the LR seems to be more sensitive, with values twice those of the PBR.

The results of the no-scenario setting show greater variability for all of the indicators studied. This is because in the absence of a scenario, the periods when the room is unoccupied are also taken into account. Consequently, the application of an occupancy scenario significantly influences the results of the indicators and therefore seems essential for processing the data correctly.

The small difference between the results obtained for the standard scenario and the adapted scenario shows that the former describes with sufficient precision the conditions of exposure to CO_2 in the house studied. This implies that using a typical scenario to test several houses without losing important information is possible if the lifestyle of the inhabitants is close to the typical scenario. However, an occupancy scenario cannot be generalized to all lifestyles.

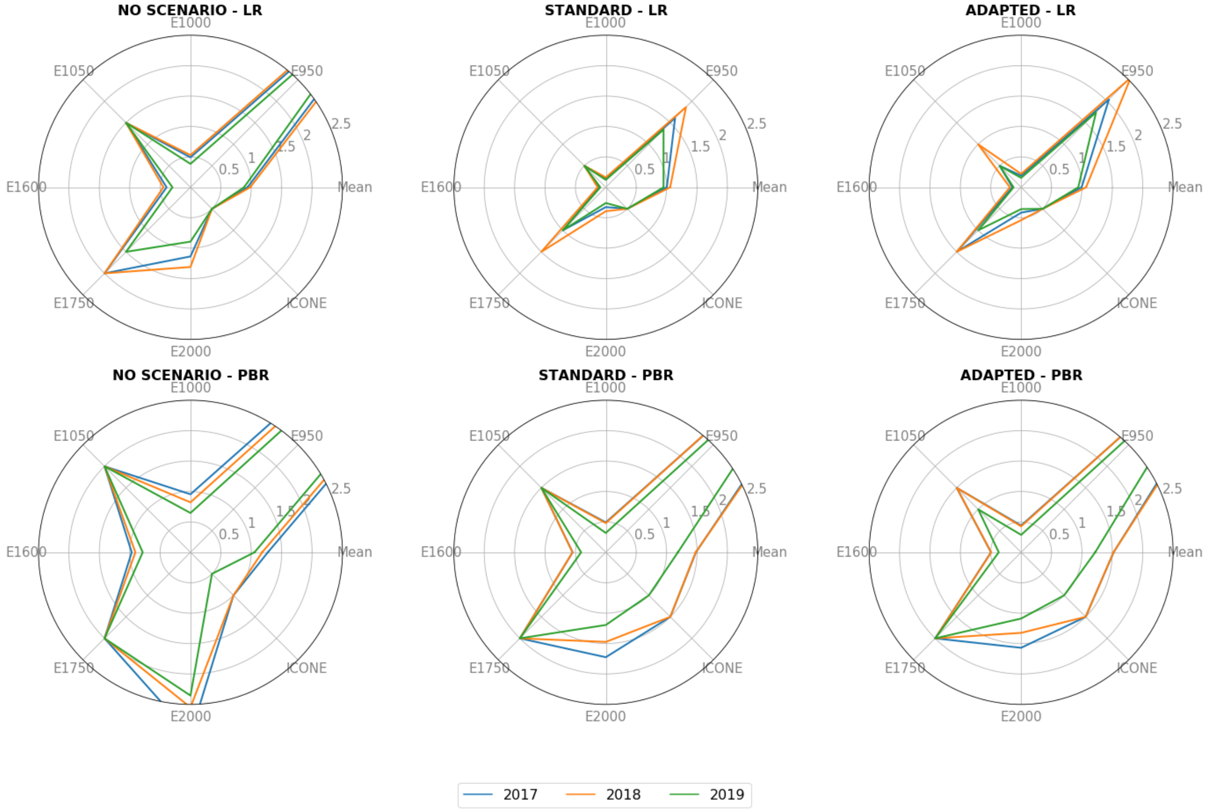


Figure 12: Radar showing the results, after normalization, of the CO_2-based IAQ indicators on House 3 with three different occupancy scenarios (no scenario, standard scenario, and adapted scenario) at the living room (LR) and at the parental bedroom (PBR).

4. Conclusions

This study has focused on the analysis and the comparison of IAQ indicators based on CO_2 measurements. It highlighted the large number of indicators proposed in the literature and provided a summary on the relevance of the information given by each indicator. Indeed, a quality indicator must be quantifiable and comparable in order to be exploitable.

A house can be characterized differently during the same period depending on the indicator, the threshold chosen, and the room evaluated (parental bedrooms usually have a higher stuffiness level than living rooms), but also depending on the occupancy scenario applied. Some results using different indicators may even be contradictory, which implies that it is not possible to replace one indicator with another. Moreover, a specific indicator can show different results for a same room through the years. That means that the habits of the inhabitants have high impact in the IAQ.

The mean concentration is the most frequent CO_2-based IAQ indicator in the literature due to its simplicity of calculation, but it leaves out the time factor. Since the dose plays a fundamental role in the IAQ, it is important to have information about the quantity of CO_2 and the amount of time above a threshold, information provided by indicators such as the cumulative exposure above a threshold value set. However, the thresholds vary from one standard to another, which makes it difficult to know which indicator best describes the conditions and risks in a room.

It is extremely important to reach a consensus to define standard indicators, thresholds and periods for the evaluation of dwellings, and in the specific case of the CO_2 parameter, to define a standard occupancy scenario. Some indicators are more sensitive to occupancy scenarios than others, especially those related to cumulative exposure above a threshold value. The results of the application of these indicators without an occupancy scenario increase up to 257% compared with the results obtained with a standard scenario.

The small difference observed between the results obtained from the application of CO_2-based IAQ indicators with a standard scenario and an adapted one (based on the real inhabitants' behavior) reinforces the relevance of implementing a standard occupancy scenario when assessing the IAQ of a building.

Future studies in positive, zero and nearly-zero energy houses, but also in houses equipped with mechanical ventilation, could aboard the variation in CO_2 concentration by the measurements of ventilation performances (flow rates, pressure differences, visual inspection, etc.) and by monitoring the opening of windows, inhabitant's habits and occupancy changes. As a perspective for this study, it is aimed to introduce this monitoring on the three houses, and to test the uncertainty of the sensors after several years of measurements. Some on-going perspectives are the calculation of comfort indicators based on the temperature and RH of the COMEPOS houses during several seasons.

Appendices

Table A1: CO_2 concentration distribution data in living rooms (LR) and parental bedrooms (PBR) of the COMEPOS houses through the years.

House	Year	LR							PBR						
		Min	Q1[b]	Mean	Median	Q3[c]	Max	IQR[d]	Min	Q1[b]	Mean	Median	Q3[c]	Max	IQR[d]
House 1	2018	396	439	494	482	537	1053	98	395	467	629	632	754	1526	288
	2019	395	446	498	488	541	987	95	396	558	712	687	828	1646	270
House 2	2017	394	490	792	640	910	3490	420	394	693	1360	1159	1856	3490	1162
	2018	394	489	769	610	825	3490	336	394	596	897	751	1008	3470	412
	2019	394	463	743	563	827	3384	364	394	706	1135	945	1352	3490	646
House 3	2017	394	599	1003	837	1190	3490	592	394	930	1482	1280	2018	3490	1088
	2018	394	652	1058	888	1271	3490	619	394	945	1478	1330	1790	3480	845
	2019	394	642	950	826	1080	3460	438	394	666	1185	932	1504	3490	838

Table A2: Maximal percentage of variation of CO_2-based IAQ results according to the indicators through years in living rooms (LR) and parental bedrooms (PBR).

House	LR												PBR											
	Mean	Median	IQR[d]	Mean above 1000 ppm	Mean above 2000 ppm	E_{950}	E_{1000}	E_{1050}	E_{1600}	E_{1750}	E_{2000}	ICONE	Mean	Median	IQR[d]	Mean above 1000 ppm	Mean above 2000 ppm	E_{950}	E_{1000}	E_{1050}	E_{1600}	E_{1750}	E_{2000}	ICONE
House 1	1	1	3	0	0	91	100	100	0	0	0	100	12	8	6	3	0	94	93	93	100	0	0	89
House 2	6	12	20	7	9	52	50	49	64	58	59	8	34	35	65	19	6	77	70	72	81	82	81	58
House 3	10	7	29	9	2	28	17	19	32	34	34	23	20	30	23	2	8	28	28	28	26	30	31	29

[b] Q1: Quartile 1
[c] Q3: Quartile 3
[d] IQR: Interquartile range

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